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Electronic Waste and Its Health Risks: An Emerging Public Health Challenge in the Digital Age

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Abstract: Background: The rapid expansion of electrical and electronic technologies has generated an unprecedented volume of electronic waste, or e-waste. Although discarded equipment contains valuable metals and reusable components, unsafe dismantling, open burning, acid leaching and uncontrolled disposal release toxic substances into workplaces and surrounding communities. **Objective:** This narrative review critically examines the health risks associated with e-waste, evaluates the current epidemiological evidence, and discusses recent advances, regulatory challenges and future priorities, with particular attention to India. **Key findings:** The world generated approximately 62 million tonnes of e-waste in 2022, but only 22.3% was documented as formally collected and recycled. Informal processing exposes workers and nearby populations to lead, mercury, cadmium, chromium, persistent organic pollutants, particulate matter and hazardous combustion products. Children, pregnant women and informal workers are especially vulnerable. Studies consistently demonstrate elevated internal exposure to toxic metals and organic pollutants in e-waste-affected populations. Reported health effects include injuries, musculoskeletal disorders, respiratory symptoms, impaired neurodevelopment, altered thyroid and reproductive hormones, adverse birth outcomes, oxidative stress and DNA damage. However, causal inference is limited by cross-sectional designs, mixed exposures, inconsistent outcome definitions and concentration of evidence in a small number of recycling communities. India has strengthened extended producer responsibility under the E-Waste (Management) Rules, 2022, but informal collection, inadequate traceability, unsafe recycling and incomplete integration of waste workers remain major concerns. **Conclusion:** E-waste should be addressed as an occupational, environmental, maternal and child health priority rather than solely as a resource-recovery problem. Effective prevention requires durable and repairable products, accountable producers, convenient collection, safe recycling, elimination of hazardous informal processes, worker protection, environmental monitoring and a just transition for informal workers.

Keywords: Electronic waste; e-waste recycling; heavy metals; occupational health; child health; extended producer responsibility

INTRODUCTION

Electrical and electronic equipment has become integral to health care, education, communication, commerce and domestic life. Mobile phones, computers, televisions, refrigerators, air conditioners, medical devices, batteries, photovoltaic equipment and numerous smaller appliances are being purchased in increasing numbers and replaced with growing frequency. When these products are discarded without an intention to reuse, they enter the electronic-waste stream.

E-waste is not a uniform material. It includes complex assemblies of metals, plastics, glass, ceramics, batteries, circuit boards and chemical additives. Many discarded products contain economically valuable materials, including copper, aluminium, iron, gold, silver, palladium and rare earth elements. The same products may also contain lead, mercury, cadmium, hexavalent chromium, brominated flame retardants, polychlorinated biphenyls and other hazardous substances. E-waste is therefore simultaneously a potential source of secondary raw materials and a toxicological hazard.

The scale of the problem is increasing faster than formal management capacity. According to the Global E-waste Monitor 2024, approximately 62 million tonnes of e-waste were generated worldwide in 2022—an increase of 82% since 2010. Only 22.3% was documented as formally collected and recycled. Global generation is projected to reach approximately 82 million tonnes by 2030 if current trends continue.[1]

The public health risk is concentrated in locations where discarded equipment is manually dismantled, burned, heated or treated with acids to recover valuable materials. Such activities are frequently undertaken by informal workers with limited protective equipment, poor ventilation and little access to occupational health services. Pollutants released at recycling sites contaminate air, household dust, soil, water, food and human tissues. The consequences extend beyond workers to families and communities, particularly children and pregnant women.[2,3]

This review examines the sources and pathways of e-waste exposure, critically appraises the evidence linking exposure with adverse health outcomes, and outlines the public health and policy responses required globally and in India.

The E-waste Chain and Hazardous Recycling Practices

The e-waste chain begins before a product is discarded. Product design determines durability, repairability, chemical composition and ease of disassembly. Marketing practices, software obsolescence, inaccessible spare parts and high repair costs may shorten useful product life. After disposal, equipment may be stored in homes, donated, resold, refurbished, transported, dismantled, recycled, exported or mixed with municipal waste.

Formal recycling facilities generally use controlled dismantling, mechanical separation, ventilation, emission controls and procedures for handling hazardous fractions. Even formal recycling is not risk-free, particularly where dust suppression, process enclosure or worker protection is inadequate. Nevertheless, the most severe exposures usually occur in informal operations.

Common informal practices include breaking devices with stones or hammers, removing components manually, burning insulated wires to recover copper, heating circuit boards, crushing cathode-ray tubes, draining refrigerants, and using strong acids to extract precious metals. Residues are often dumped onto soil, into drains or in nearby water bodies. WHO identifies open burning and heating as particularly hazardous because they generate toxic fumes and contaminate air, dust, soil and water.[2]

Mechanical dismantling releases contaminated dust containing lead, cadmium and other metals. Open burning of plastic-coated wires produces fine particulate matter, polycyclic aromatic hydrocarbons, dioxins, furans and brominated compounds. Acid leaching exposes workers to corrosive chemicals and metal-containing fumes while producing highly contaminated liquid waste. Refrigerators and cooling equipment may release refrigerants and insulating agents that damage the climate and, depending on the substance, may pose acute occupational hazards.

Landfilling does not neutralize these materials. Over time, metals and additives may migrate into leachate, particularly where waste is deposited in unlined dumps. Informal recycling locations can therefore become persistent sources of environmental exposure even after visible processing activities decline.

Exposure Pathways and Vulnerable Populations

Exposure occurs through inhalation of fumes and dust, ingestion of contaminated food, water or soil, dermal contact and transplacental or breast-milk transfer. Workers may carry contaminated dust home on their skin, clothing, shoes and tools, creating secondary exposure among family members.

Informal workers are exposed directly during collection, dismantling, burning, sorting and metal recovery. Their risks are not limited to chemical toxicity. Sharp edges, broken glass, heavy equipment, repetitive lifting, excessive noise, heat, electrical hazards, fires and corrosive chemicals cause injuries and musculoskeletal disorders. Workers may also lack job security, social protection, washing facilities and access to medical care.

Children are especially susceptible because of their developing nervous, immune, respiratory and endocrine systems. They breathe more air and consume more food relative to body weight than adults, frequently place their hands or objects in their mouths, and spend time close to contaminated soil and household dust. Some children participate directly in waste picking, sorting or burning. WHO has warned that millions of children and women may be at risk in informal waste-processing environments.[2]

Pregnancy represents another critical window. Lead, mercury and several persistent organic pollutants can cross the placenta, while some lipophilic compounds may be transferred through breast milk. Prenatal exposure may affect fetal growth, neurodevelopment, endocrine regulation and pregnancy outcomes. The degree of risk depends on pollutant concentration, timing of exposure, nutritional status, co-exposures and maternal susceptibility.

Communities living near recycling areas may be exposed even when they do not work with e-waste. Polluted dust may enter homes and schools, while locally produced vegetables, fish, poultry or livestock can accumulate contaminants. This community-wide distribution makes the simple classification of individuals as "workers" and "non-workers" inadequate.

Toxic Constituents and Biological Effects

Lead and other toxic metals

Lead is present in solder, circuit boards, cathode-ray tube glass, batteries and older electronic components. It interferes with synapse formation, haem synthesis, calcium-mediated signalling and multiple enzymatic processes. No safe level of childhood lead exposure has been established. Children exposed near e-waste sites have repeatedly shown higher blood lead concentrations than comparison populations.

A 2023 systematic review of 20 studies found that most investigations reported blood lead levels of at least 5 μg/dL among children exposed in e-waste environments. Reported outcomes included impaired haemoglobin synthesis, altered neurobehavioural development, effects on physical growth, oxidative damage and endocrine changes.[5] However, most included studies were conducted in Chinese recycling areas, limiting geographical generalizability.

Cadmium is nephrotoxic and may affect bone, cardiovascular and reproductive health. Mercury damages the developing nervous system, while hexavalent chromium is an irritant and carcinogen. Arsenic, nickel, manganese and antimony may also be encountered. Because workers are exposed to mixtures, assigning an observed outcome to a single metal is often impossible.

Persistent organic pollutants and combustion products

Plastics and electrical components may contain brominated flame retardants, including polybrominated diphenyl ethers. Older equipment may contain polychlorinated biphenyls, while uncontrolled combustion generates dioxins, furans and polycyclic aromatic hydrocarbons. These compounds may persist in the environment, accumulate in food chains and interfere with endocrine, immune, reproductive and neurological systems.

Open burning also generates fine particulate matter and irritant gases. Particles can penetrate deep into the lungs, produce oxidative stress and contribute to systemic inflammation. Workers involved in burning and nearby residents may therefore face overlapping risks from toxic chemicals and conventional air pollutants.

Mixed exposure and toxicological uncertainty

The health risk posed by e-waste cannot be adequately understood by examining individual substances in isolation. Exposure profiles vary according to the device being processed, work task, temperature, duration, recycling method and local environment. Metals may interact with persistent organic pollutants, air pollution, nutritional deficiencies and infectious or psychosocial stressors.

This complexity has two implications. First, biomonitoring of a single chemical may underestimate the total hazard. Second, statistically significant associations with one pollutant may reflect correlated exposure to several others. Studies require mixture-based analytical approaches, but these remain uncommon.

Evidence on Health Outcomes

Occupational injuries and musculoskeletal disorders

Injuries and musculoskeletal problems are among the most immediately credible consequences of informal recycling. Cuts, puncture wounds, burns, eye injuries, electric shocks and falls result directly from unsafe tools, broken components and unprotected handling. Repetitive dismantling, prolonged squatting, awkward posture and manual transportation of heavy equipment contribute to back, neck and limb pain.

A 2024 systematic review focused specifically on informal e-waste workers found recurring evidence of musculoskeletal pain, injuries, respiratory complaints, hearing problems and several biochemical abnormalities. However, the authors concluded that only musculoskeletal disorders and work-related injuries could be attributed relatively directly to occupational activities; causal evidence for many chronic outcomes remained insufficient because most studies were cross-sectional and heterogeneous.[6]

Respiratory and cardiovascular effects

Workers frequently report cough, sputum production, breathlessness, chest discomfort and eye or throat irritation. Dust, smoke, metal fumes and acidic vapours provide a strong biological basis for respiratory injury. Some studies have reported reduced lung-function parameters, but evidence for clinically defined chronic respiratory disease remains limited by short follow-up and inadequate control for tobacco smoke, ambient pollution and occupational co-exposures.

Cardiovascular findings include altered blood pressure, heart-rate abnormalities, oxidative stress and changes in lipid profiles. These associations are plausible given exposure to lead, cadmium and particulate matter, but robust prospective evidence linking e-waste exposure to cardiovascular events is not yet available.

Neurodevelopment and child health

Neurodevelopmental effects are a central concern because lead, mercury, manganese and several organic pollutants can interfere with brain development. Studies from exposed communities have reported altered temperament, impaired sensory integration, reduced memory performance, changes in thyroid hormones and developmental deficits.[3,5]

The updated systematic review by Parvez and colleagues included 70 studies and found that residents of e-waste-exposed areas generally had higher concentrations of heavy metals and persistent organic pollutants. Children and pregnant women were identified as particularly susceptible, with evidence suggesting adverse effects on neonatal growth and hormone regulation.[3]

Nevertheless, developmental outcomes are influenced by nutrition, parental education, poverty, home stimulation and exposure to other environmental toxicants. Many studies do not measure these factors adequately. The evidence supports serious concern and preventive action, but precise estimates of the neurodevelopmental burden attributable solely to e-waste remain unavailable.

Reproductive, endocrine and perinatal outcomes

Studies have associated e-waste exposure with altered thyroid hormones, changes in sex hormones, reduced semen quality, spontaneous abortion, stillbirth, premature delivery, lower birth weight and impaired neonatal growth.[3,7] The earlier systematic review by Grant and colleagues identified plausible associations across reproductive, developmental and endocrine outcomes, although the evidence was already recognized as methodologically heterogeneous.[7]

More recent research strengthens evidence of internal contamination but has not fully resolved causality. Maternal age, parity, nutrition, antenatal care, socioeconomic status and exposure to other pollutants can influence pregnancy outcomes. Furthermore, “e-waste exposure” often represents a poorly characterized mixture rather than a measured dose.

Genotoxicity, cancer and chronic disease

Biomarker studies have reported oxidative DNA damage, chromosomal abnormalities and altered gene expression among exposed populations. Several e-waste pollutants are established or suspected carcinogens. However, direct evidence linking informal e-waste exposure to incident cancer is weak. Cancer requires long follow-up, reliable exposure reconstruction and large populations—conditions rarely met in existing studies.

Claims that e-waste exposure has been proven to cause particular cancers should therefore be avoided. Current evidence establishes hazardous exposure and biological plausibility, but not reliable cancer-risk estimates.

Public Health Significance

E-waste illustrates how the benefits and harms of technological development are distributed unequally. Consumers may enjoy frequent device replacement, while discarded products are processed by workers who receive little protection and retain only a small share of their economic value. Hazardous recycling in low-income communities is therefore an issue of environmental justice.

Table 1. E-waste Processes, Exposures, Health Risks and Public Health Controls

E-waste activity or source	Main hazardous exposures	Potential or documented health effects	Strength and limitations of evidence	Priority controls
Manual dismantling and breaking	Lead- and metal-contaminated dust, sharp objects, broken glass and noise	Cuts, eye injuries, musculoskeletal pain, respiratory irritation, lead exposure and hearing problems	Strong evidence for injuries and ergonomic harm; chronic disease evidence is mainly cross-sectional	Enclosed workstations, local exhaust ventilation, safer tools, gloves, eye protection and noise control
Open burning of wires and plastics	$PM_{2.5}$, PAHs, dioxins, furans, brominated compounds and metal fumes	Acute respiratory symptoms, inflammation, neurological and endocrine toxicity; possible long-term carcinogenic risk	Strong toxicological plausibility; limited long-term epidemiological follow-up	Prohibit open burning, provide mechanical separation and enforce emission controls
Heating circuit boards	Lead fumes, tin, brominated flame retardants and combustion products	Neurological, respiratory, reproductive and endocrine effects	Exposure documented; outcome attribution complicated by pollutant mixtures	Temperature-controlled enclosed processes, ventilation and exposure monitoring
Informal acid leaching	Strong acids, dissolved metals, corrosive vapours and contaminated wastewater	Burns, eye injury, respiratory irritation, systemic metal exposure and environmental contamination	Acute hazards are clear; long-term effects poorly quantified	Closed-loop hydrometallurgical systems, chemical handling protocols and wastewater treatment
Cathode-ray tube breaking	Leaded glass, phosphor dust and sharp glass	Lacerations, lead exposure, eye injury and respiratory irritation	Lead exposure is biologically well established; data on task-specific health outcomes remain limited	Specialized collection and enclosed dismantling
Informal refrigerator and air-conditioner processing	Refrigerants, compressor oils, foams, metals and sharp components	Acute injury, chemical exposure and climate-related harms from released refrigerants	Occupational studies are sparse	Refrigerant recovery, technician training and controlled degassing
Dumping or landfilling	Metal-containing leachate, contaminated soil and persistent chemicals	Chronic community exposure through water, soil, food and household dust	Environmental contamination is well documented; human dose and outcome relationships vary	Secure storage, lined disposal for hazardous residues and long-term monitoring
Household take-home contamination	Dust carried on clothing, tools and skin	Childhood lead exposure and prenatal or family exposure	Plausible and demonstrated in other hazardous industries; e-waste-specific evidence is emerging	Changing facilities, workplace laundering, showers and separation of work from living areas
Formal	Dust, noise,	Occupational	Lower expected	Independent audits,

recycling with inadequate controls	repetitive work and residual hazardous fractions	injury, respiratory symptoms and metal exposure	risk than informal recycling, but compliance varies	exposure limits, health surveillance and verified downstream disposal

The problem also has implications for health systems. Hospitals and laboratories generate discarded monitors, imaging equipment, diagnostic instruments and electronic accessories. Health-care institutions should maintain inventories, protect data stored on devices, and ensure transfer only to authorized recyclers. Health professionals can identify occupational exposure, diagnose metal toxicity, counsel pregnant women and advocate for safer recycling.

E-waste management also supports climate and resource security. Recovering metals from discarded electronics may reduce some demand for environmentally destructive primary mining. However, recycling cannot compensate indefinitely for rising consumption and shortened product life. Waste prevention, repair, refurbishment and reuse must precede material recovery.

Indian Perspective

India's expanding digital economy, appliance ownership, telecommunications network and renewable-energy sector are increasing the volume and complexity of e-waste. CPCB estimates reported by the Government of India indicate that approximately 1.254 million tonnes of e-waste were generated in 2023–2024 and 1.398 million tonnes in 2024–2025 under the equipment categories covered by the current rules.[9] These figures are modelled from registered producer sales and average product life and should not be interpreted as a complete physical count of every discarded device.

The E-Waste (Management) Rules, 2022, effective from April 1, 2023, introduced a revised extended producer responsibility system. Producers, manufacturers, refurbishers and recyclers must register on a centralized CPCB portal. Producers meet recycling obligations through certificates generated by registered recyclers, while the rules provide for audit, verification and environmental compensation.[8,9]

The framework represents an important shift towards traceability and producer accountability. Nevertheless, certificate-based systems can become administratively compliant without ensuring that the underlying waste has been safely collected and processed. Risks include inflated recycling claims, double counting, inadequate verification of material flows and concentration on high-value fractions while hazardous residues remain poorly managed.

India's informal sector remains central to collection because itinerant buyers and scrap dealers offer convenient doorstep service and immediate payment. Formal systems may be technically safer but often have weaker collection networks. Attempting to eliminate informal workers without providing alternative livelihoods could drive activities underground and weaken recovery. Policy should integrate collectors and dismantlers through registration, training, cooperatives, buy-back arrangements and formal partnerships while prohibiting hazardous practices such as burning and acid leaching.

Recent Advances

Recent e-waste policy increasingly incorporates circular-economy principles. "Right-to-repair" initiatives, longer warranties, standardized components, software support, modular design and availability of spare parts can extend product life. Digital product passports may eventually provide information on composition, repairability, hazardous substances and recycling pathways.

Advances in mechanical, hydrometallurgical and bio-metallurgical recovery offer alternatives to uncontrolled burning and acid extraction. Automated sorting and robotics may reduce direct worker contact, although their feasibility depends on investment, scale and product standardization. Cleaner technology must be assessed across its full life cycle because sophisticated recycling can itself consume energy and chemicals.

Portable X-ray fluorescence, personal air sampling, wearable sensors and multi-element biomonitoring can improve exposure characterization. Statistical methods for analysing chemical mixtures are also developing. Yet these advances will have limited impact unless applied in informal settings and linked with clinical and environmental interventions.

Challenges and Limitations

The epidemiological literature remains geographically concentrated, particularly in China, Ghana and a small number of other informal recycling centres. Evidence from India is comparatively fragmented despite a large informal workforce. Findings from heavily contaminated sites may not apply directly to all e-waste settings.

Most studies are cross-sectional, preventing determination of whether exposure preceded disease. Participants are often selected through convenience sampling, and comparison communities may differ in income, nutrition, occupation and ambient pollution. Occupational categories are frequently combined despite large differences between collectors, dismantlers, burners and acid leachers.

Exposure assessment is another major weakness. Residence near a recycling site or employment as an e-waste worker does not quantify individual dose. Biomarkers improve measurement but may reflect other sources of lead, mercury or persistent pollutants. Single measurements cannot reconstruct cumulative exposure or critical developmental windows.

Health outcomes also vary widely. Studies report symptoms, biochemical markers, hormone concentrations, birth outcomes and developmental assessments using different definitions. This heterogeneity limits meta-analysis and burden estimation. The evidence is sufficient to establish preventable hazardous exposure but remains inadequate for precise predictions of many disease outcomes.

Future Directions

Research should move towards prospective cohorts that measure exposure before disease onset. Pregnant women and children should be followed through critical developmental periods, with repeated measurement of metals, organic pollutants, growth, cognition, endocrine function and respiratory health. Occupational cohorts require long-term surveillance for chronic respiratory, neurological, renal, cardiovascular and malignant disease.

Studies should analyse exposures as mixtures and differentiate recycling tasks. Environmental sampling of air, water, soil, food and household dust should be linked with personal monitoring and biomarker data. Standardized case definitions and reporting frameworks would permit comparisons across countries.

India requires independent material-flow studies that track e-waste from consumer to final recovery or disposal. The EPR portal should be supported by risk-based audits, random physical verification, publicly accessible data and clear accounting of hazardous residues. Formal recycling capacity should be evaluated by actual safe throughput rather than registered capacity alone.

Worker protection should include vaccination, injury care, respiratory assessment, hearing conservation, blood-lead testing where indicated, reproductive-health safeguards, hygiene facilities and access to health insurance. Children and pregnant women should not be involved in hazardous processing.

Ultimately, prevention must begin at the design stage. Producers should be required to minimize hazardous materials, support repair, maintain software, provide spare parts and finance convenient collection. Public procurement can accelerate change by favouring durable, repairable and recyclable equipment.

CONCLUSION

E-waste is one of the defining environmental health challenges of the digital era. The same discarded products that contain valuable metals also release neurotoxic, nephrotoxic, endocrine-disrupting and carcinogenic substances when dismantled, burned or leached under unsafe conditions.

The evidence is strongest for widespread environmental contamination, elevated body burdens of hazardous chemicals, occupational injuries and musculoskeletal disorders. Associations with impaired neurodevelopment, altered hormones, adverse pregnancy outcomes, respiratory disease, reproductive effects and genotoxicity are concerning, but the precise causal contribution of e-waste remains difficult to quantify because exposures are mixed and most studies are cross-sectional.

India's revised extended producer responsibility framework provides an important regulatory foundation, but success will depend on traceable material flows, credible audits, convenient collection, safe treatment of hazardous residues and meaningful integration of informal workers. Merely shifting waste from an unregistered worker to a registered entity does not guarantee health protection.

A sustainable response must combine prevention, repair, reuse, formal recycling and occupational safeguards. The central public health objective is not simply to recover more metals, but to ensure that the digital economy does not transfer its toxic costs to workers, children and communities least able to bear them.

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